Present and future high energy accelerators at CERN

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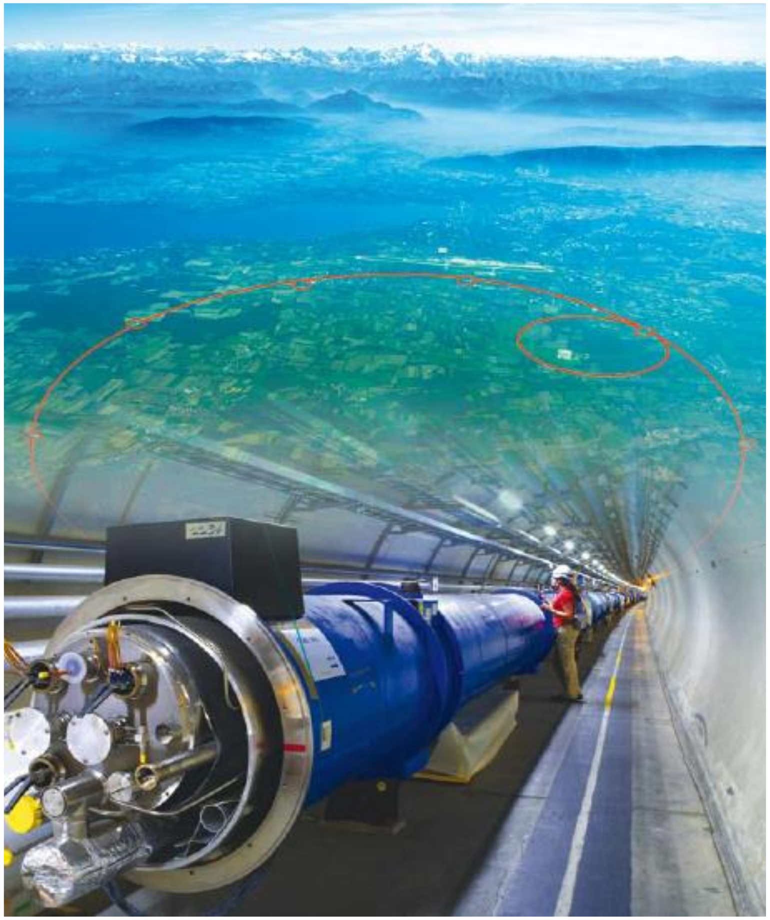
NuPECC Meeting
10th March 2017

www.cern.ch

LHC (Large Hadron Collider)

14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions



1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval of the LHC by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000 : Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007 : Magnets Installation in the tunnel
2006-2008 : Hardware commissioning
2008-2009 : Beam commissioning and repair

2010-2035: Physics exploitation

2010 – 2012 : Run 1 ;7 and 8 TeV

2015 – 2018 : Run 2 ; 13 TeV

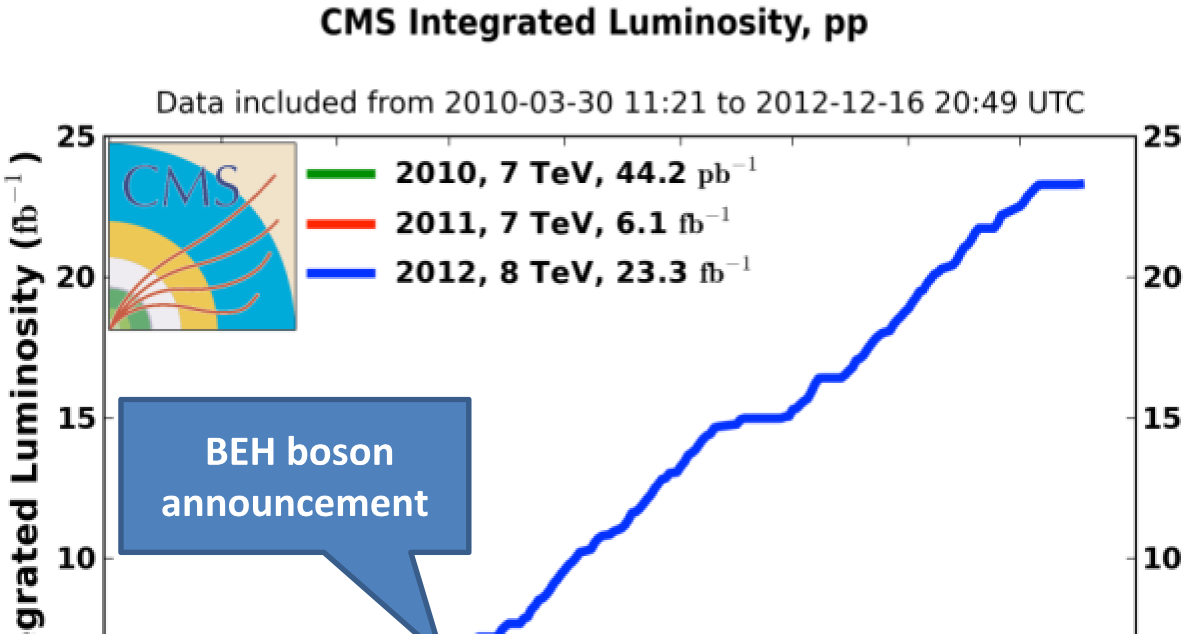
2021 – 2023 : Run 3 (13 TeV – 14 TeV)

2024 – 2025 : HL-LHC installation

2026 – 2035… : HL-LHC operation

A 27 km circumference collider…

LHC 2010-2012: a rich harvest of collisions



Σ ~30 fb^{-1}

2010: **0.04 fb^{-1}**
7 TeV CoM
Commissioning

2011: **6.1 fb^{-1}**
7 TeV CoM
… exploring limits

2012: **23.3 fb^{-1}**
8 TeV CoM
… production

7 TeV and 8 TeV in 2012
Up to 1380 bunches
with1.5 10^{11} protons

2013 - 2015

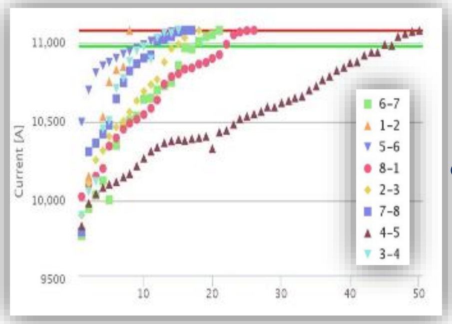
28th October
Physics with record number of bunches
Peak luminosity 5 x 10^{33} $cm^{-2}s^{-1}$

April ‘13 to Sep. ‘14

3rd June
First Stable Beams

5th April

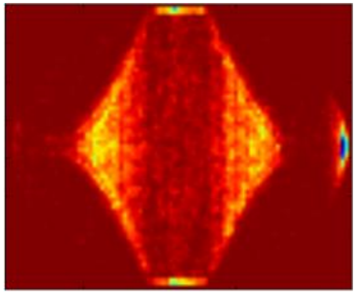
13-14 | Aug 14-Apr | 2015



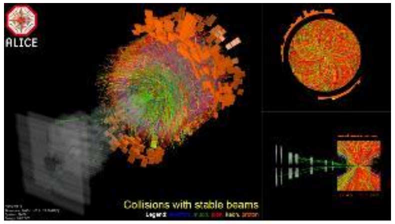
Dipole training campaign

10th April
Beam at 6.5 TeV

Struggle



IONS

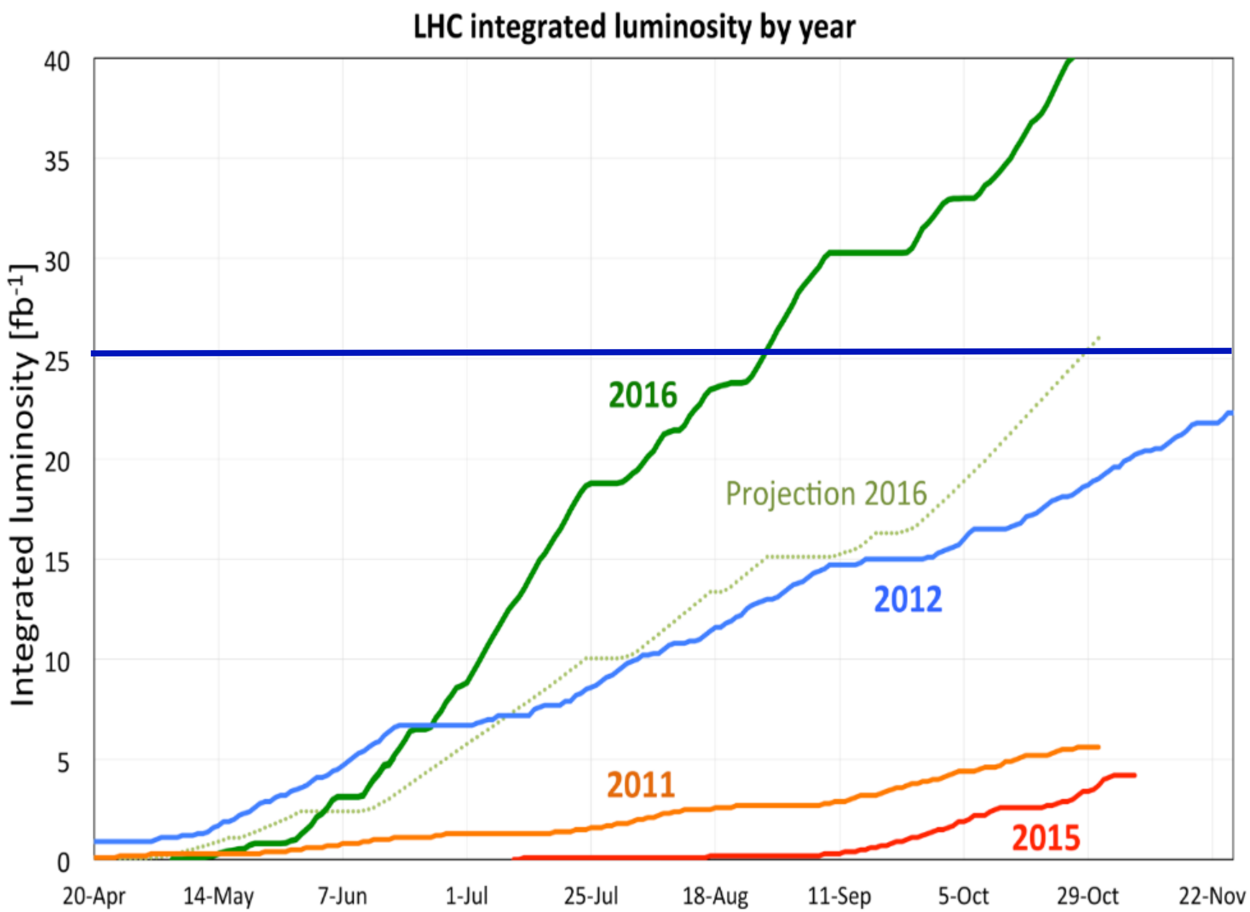


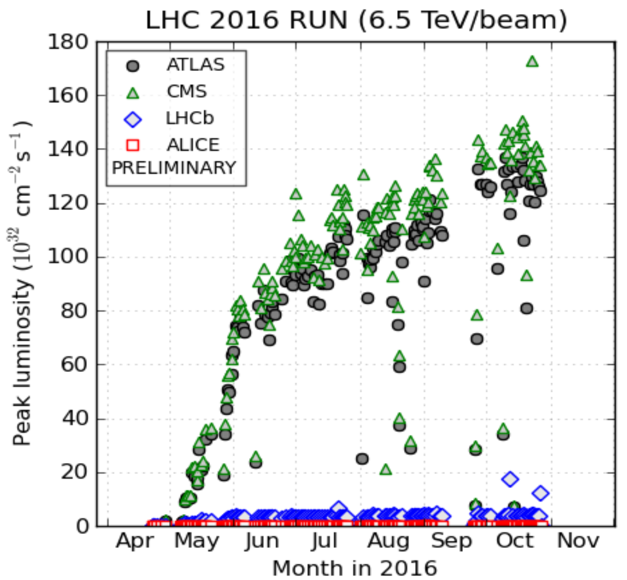
Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

2016 LHC

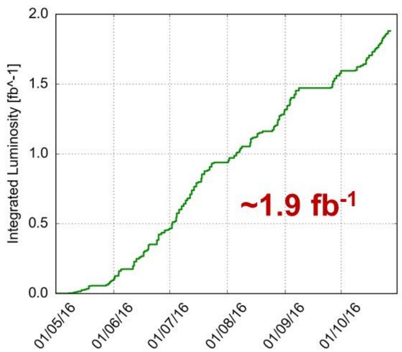
Peak luminosity > 1.4 x 10^{34} $cm^{-2}s^{-1}$

OVER 25 fb^{-1} in both ATLAS and CMS ☺

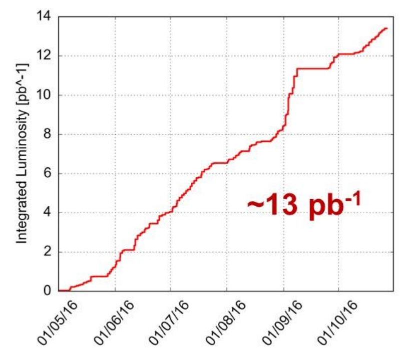




LHCb

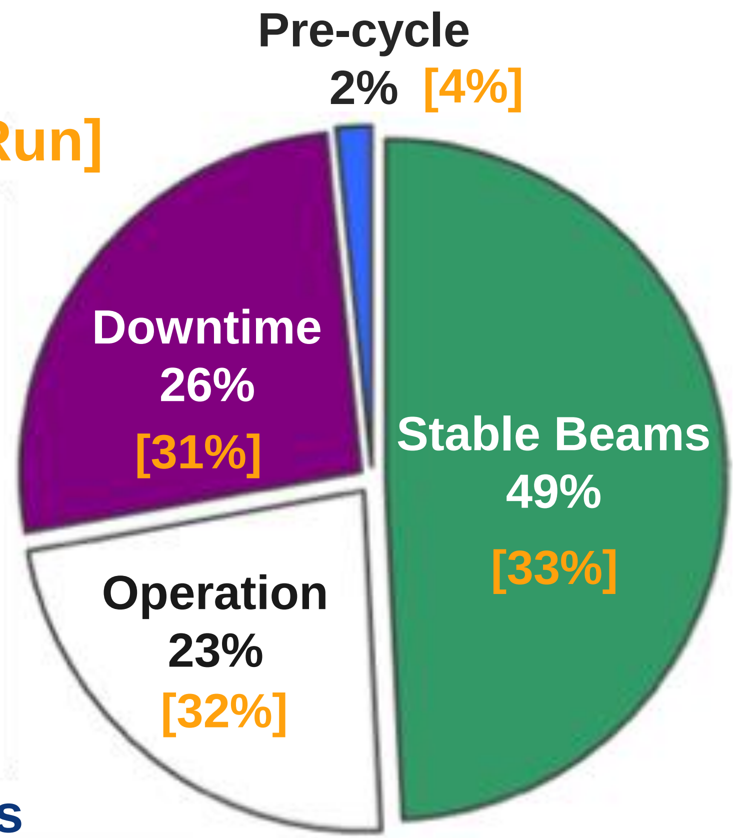


ALICE



2016 Availability

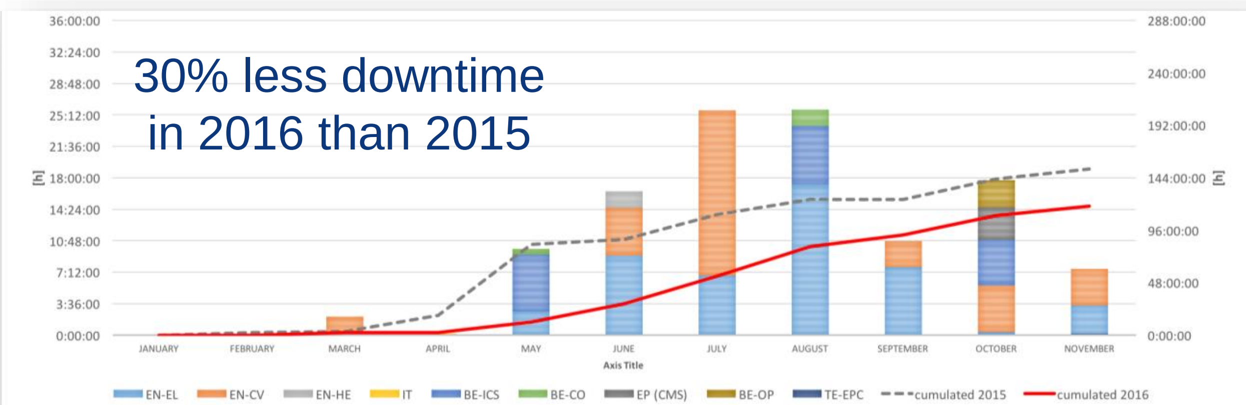
[2015 - 25 ns Run]



Remarkable availability:

- **Increased** operational efficiency
- **Enhanced** system availability
- **New** pre-cycle strategy

Downtime of technical infrastructures

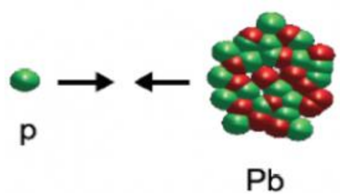


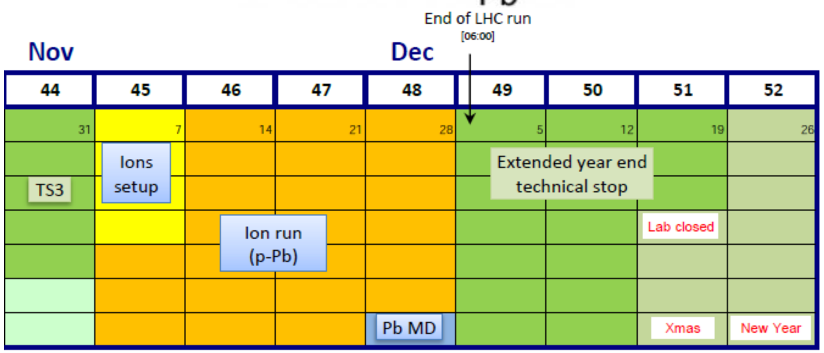
Non-availability of beams from the injector complex is the largest source of LHC downtime

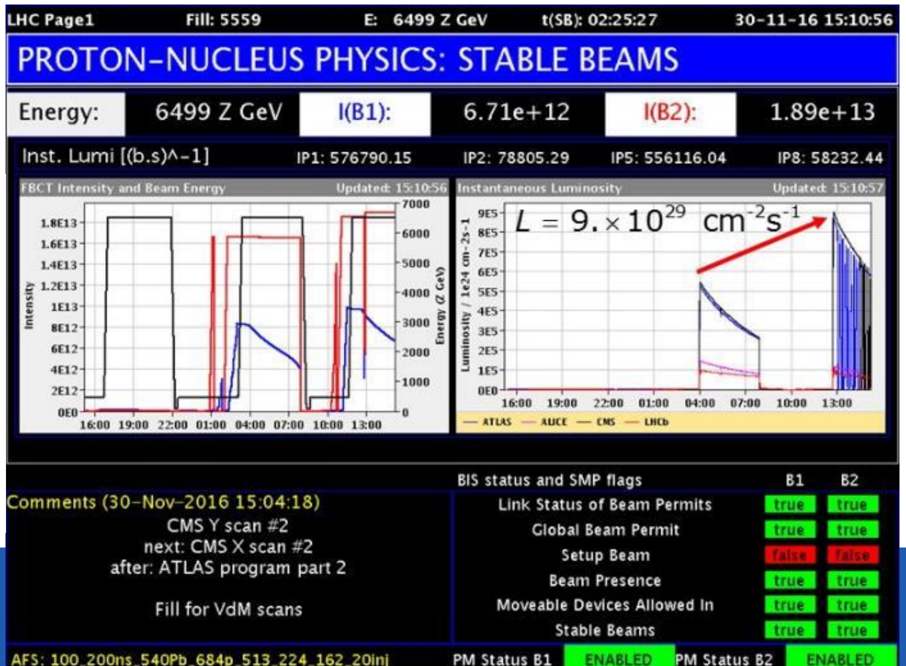
TS1 - TS2 : stable beams 58 %
TS2 - TS3 : stable beams 54 %

2016 LHC p-Pb run

Configuration	Goal		Achieved
5 TeV p-Pb **(E_{beam}=4 Z TeV)**	ALICE	700×10^{6} min bias events	**780×10^{6}**
8 TeV p-Pb **(E_{beam}=6.5 Z TeV)**	ATLAS - CMS	50 nb^{-1}	**69.5 - 65.5 nb^{-1}**
	LHCb - ALICE	10 nb^{-1}	**14 - 13 nb^{-1}**
	LHCf	9-12 h at 10^{28} $cm^{-2}s^{-1}$	**9.5 h**
8 TeV Pb-p **(E_{beam}=6.5 Z TeV)**	ATLAS - CMS	50 nb^{-1}	**124 - 118 nb^{-1}**
	ALICE - LHCb	10 nb^{-1}	**25 - 19 nb^{-1}**







LHC Limitations

SPS beam-dump

Nb of bunches per injection limited to 96

Total number of bunches: 2200

LHC Injection kickers

Outgassing from ceramic

Bunch population limited to around 1.1 x 10^{11}

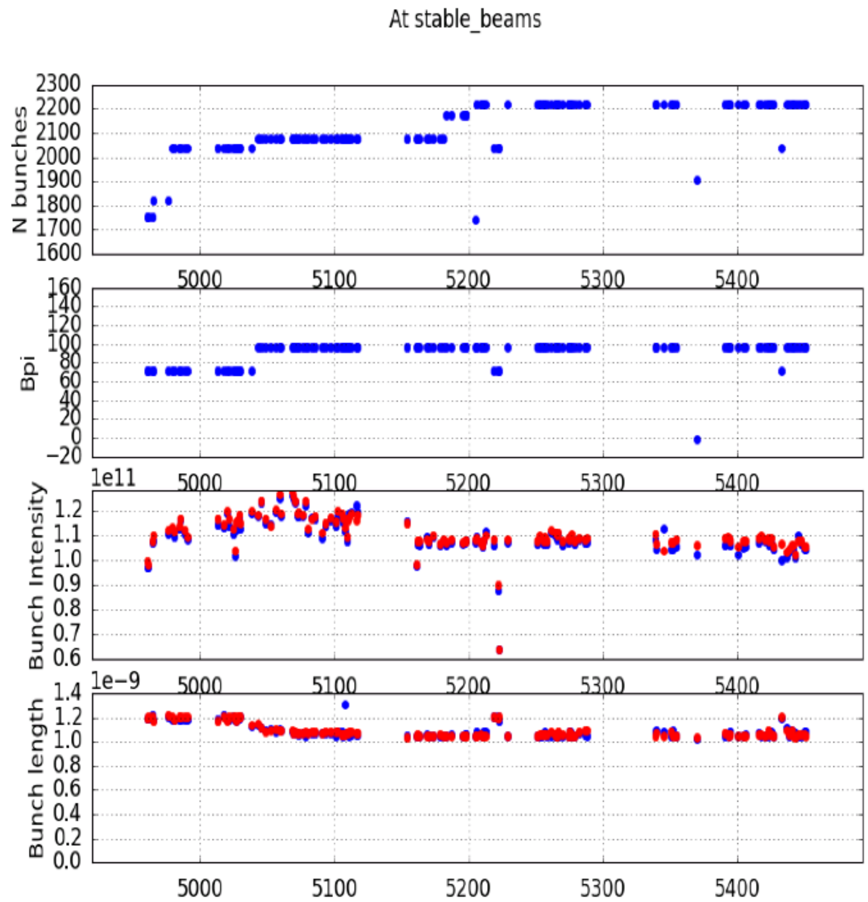
Electron cloud

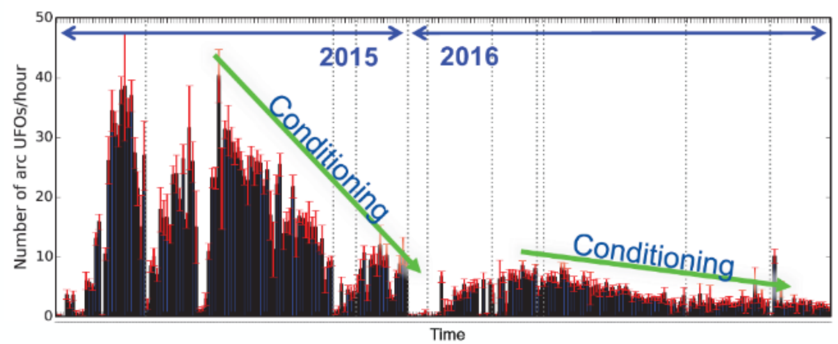
Still significant heat-load within cryogenic limits

Dynamics – well handled by cryogenics feed-forward – no impact on operations in the present conditions

UFOs

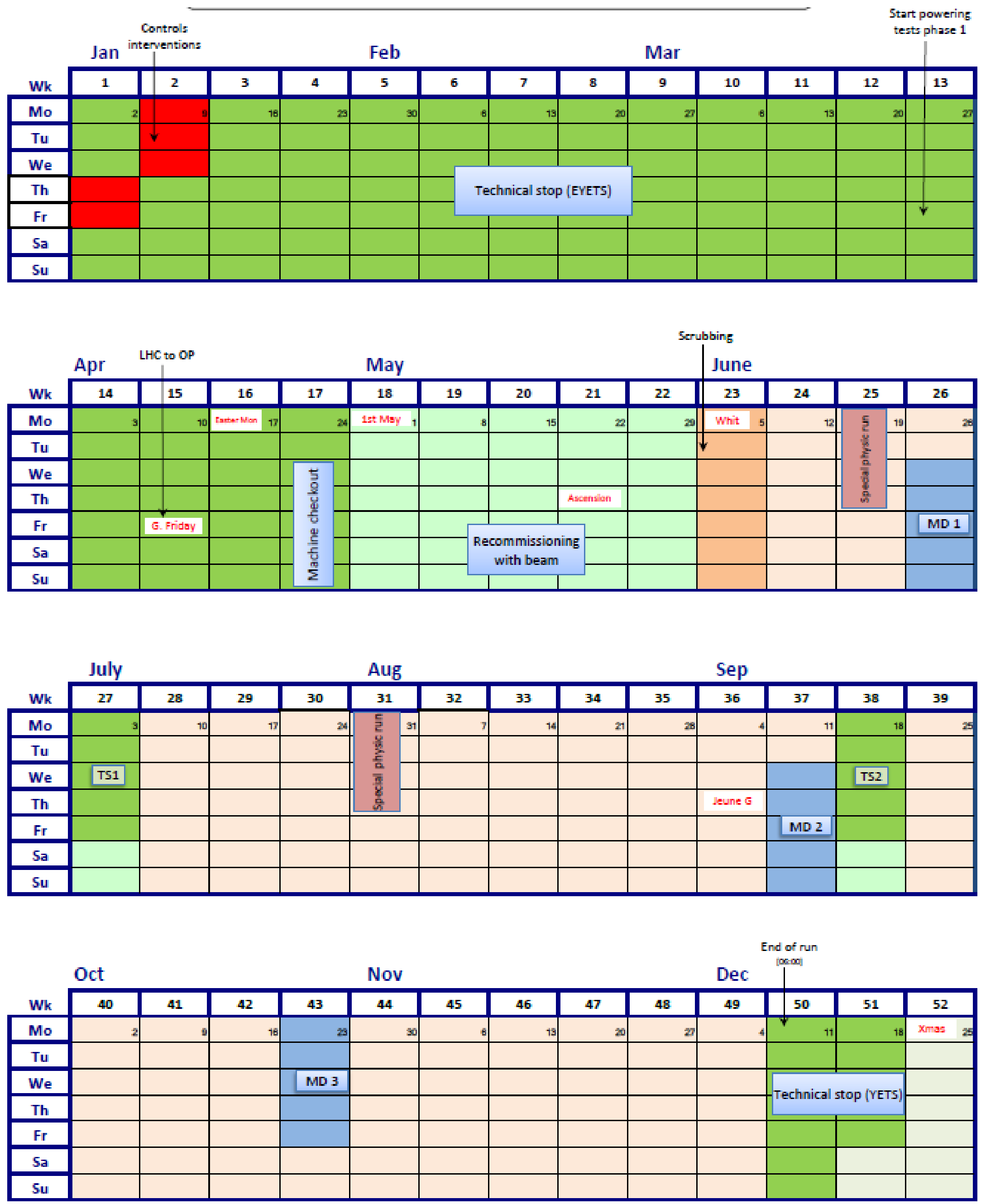
Frequency has happily conditioned down





LHC schedule 2017

a new production year at 13 TeV



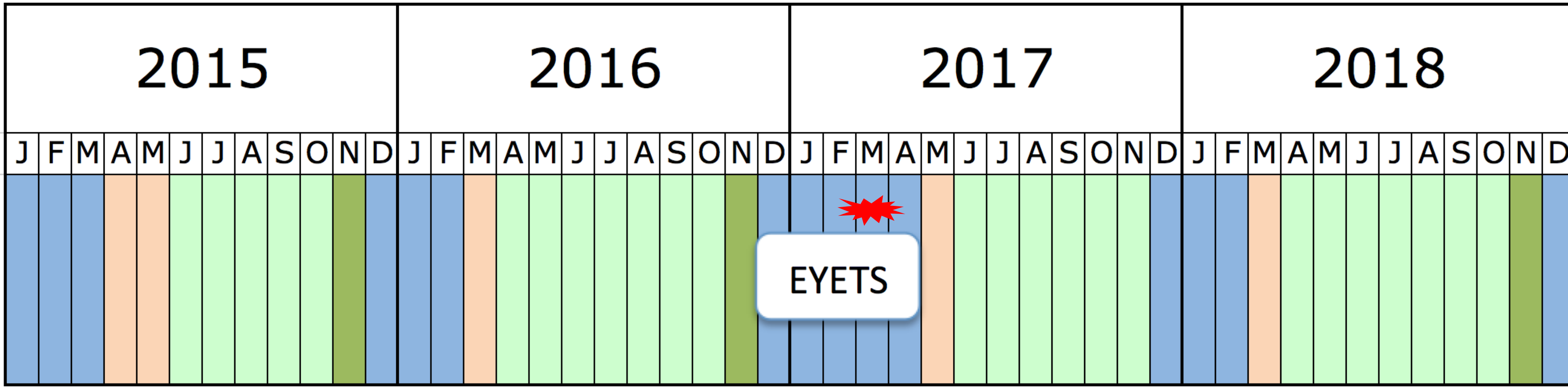
Goal 45fb^{-1}

keeping the LHC availability close to 50% (stable beams)

145 p-p physics days

Run 2 and Run 3

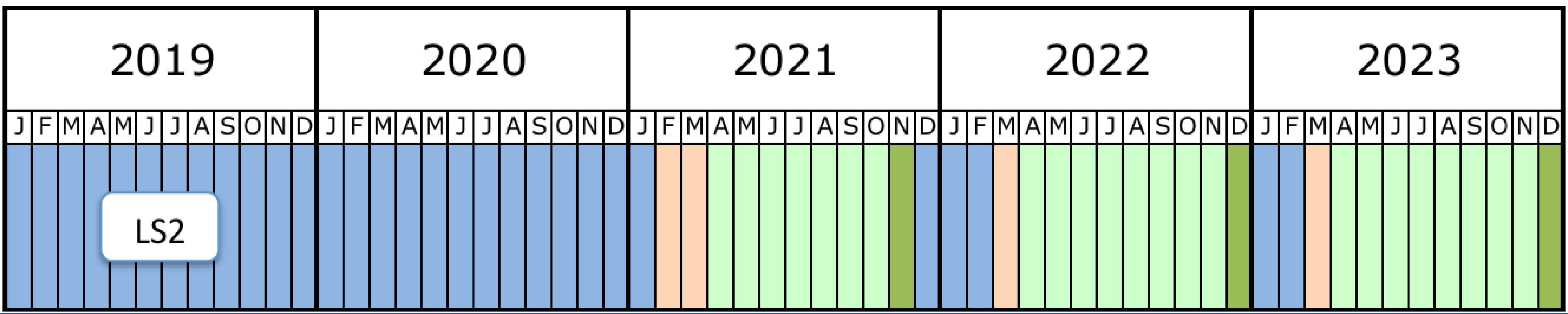
Ion runs end of 2018 (Pb-Pb)



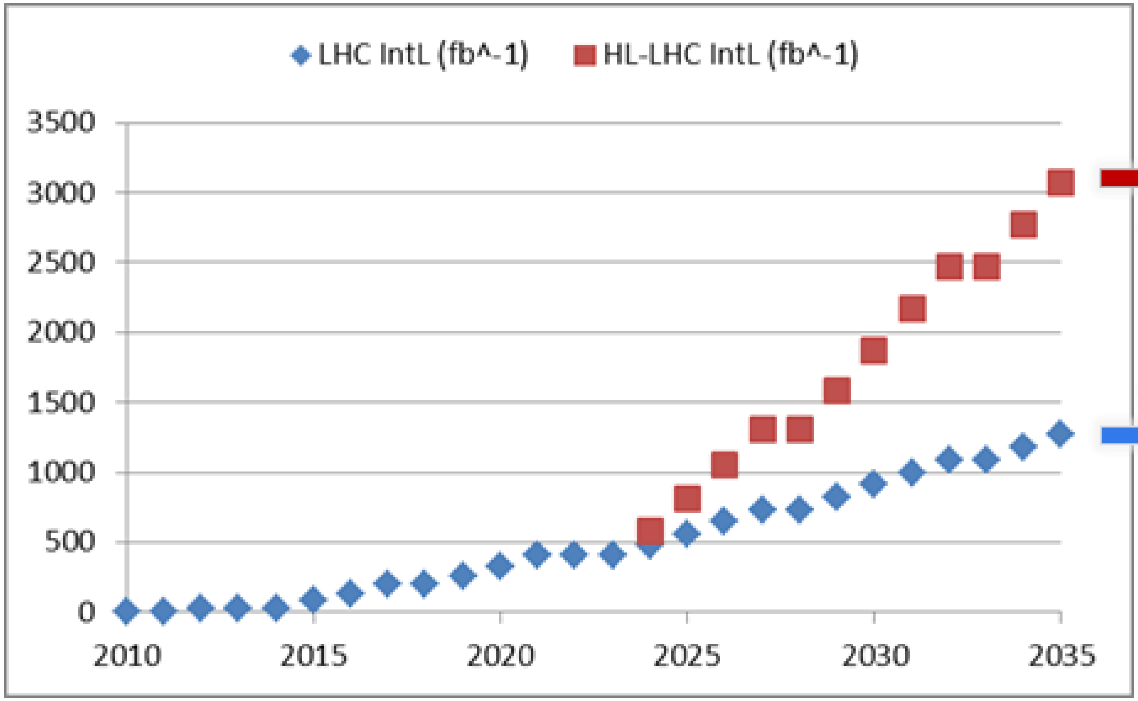
- Shutdown/Technical stop
- Protons physics
- Commissioning
- Ions

>120 fb^{-1} (13 TeV)

Σ 300 fb^{-1} (14 TeV ?)



Why High-Luminosity LHC ? (LS3)



By implementing HL-LHC

Almost a factor 3

By continuous performance improvement and consolidation

Around 300 fb^{-1} the present Inner Triplet magnets reach the end of their useful life (due to radiation damage) and must be replaced.

Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- **3000 fb^{-1} in about 10 years**

European Strategy for Particle Physics

The European Strategy for Particle Physics
Update 2013

*Europe's top priority should be the **exploitation of the full potential of the LHC**, including the high-luminosity upgrade of the machine and detectors with a view to collecting **ten times more data than in the initial design, by around 2030**. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

HL-LHC from a study to a PROJECT

300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU**

(Linac 4, Booster 2GeV, PS and SPS upgrade)

Goals and means of the LHC Injectors Upgrade: LIU project

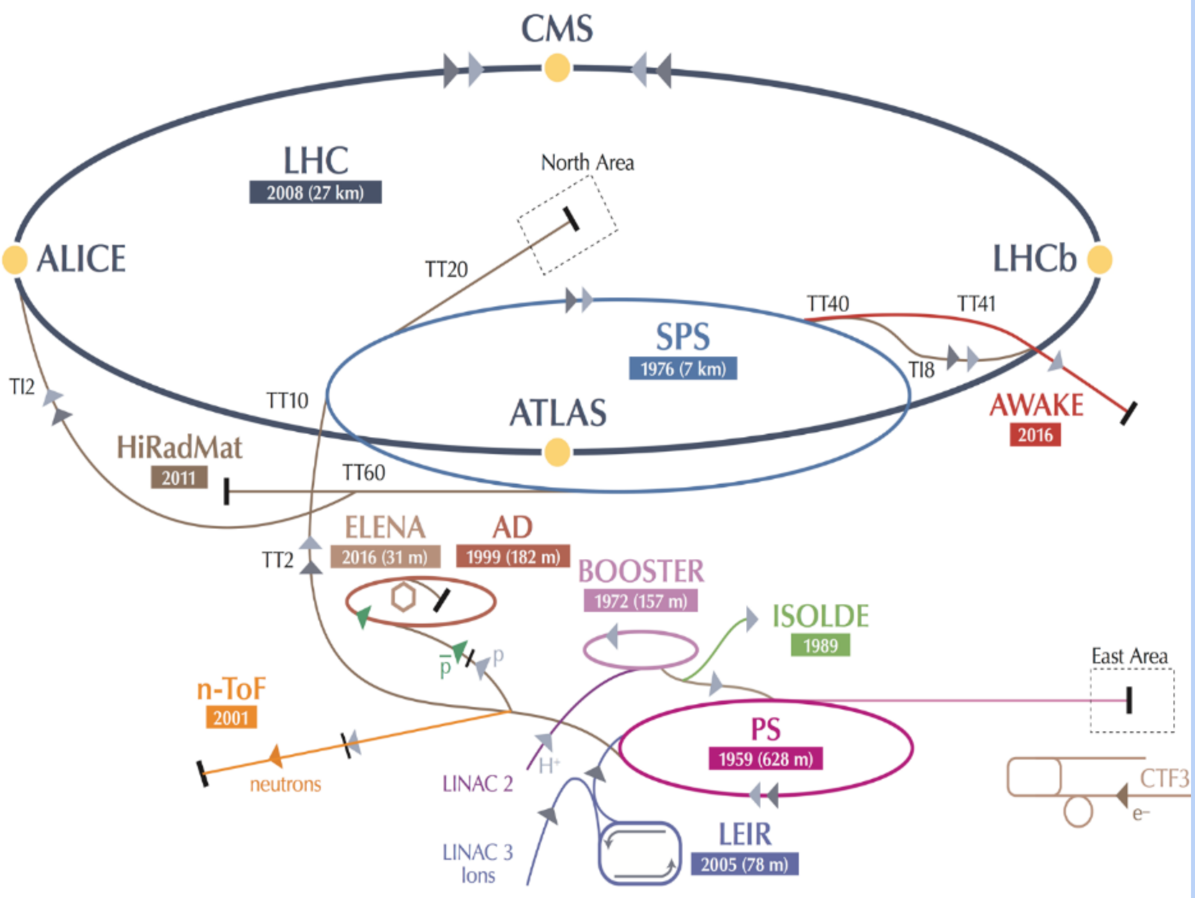
Increase injector reliability and lifetime to cover HL-LHC run (until ~2035) closely related to consolidation program

⇒ Upgrade/replace ageing equipment (power supplies, magnets, RF…)
⇒ Improve radioprotection measures (shielding, ventilation…)

Increase intensity/brightness in the injectors to match HL-LHC requirements

⇒ Enable Linac4/PSB/PS/SPS to accelerate and manipulate higher intensity beams (efficient production, space charge & electron cloud mitigation, impedance reduction, feedbacks, etc.)
⇒ Upgrade the injectors of the ion chain (Linac3, LEIR, PS, SPS) to produce beam parameters at the LHC injection that can meet the luminosity goal

CERN's scientific diversity programme



~20 experiments, > 1200 physicists

AD: Antiproton Decelerator for antimatter studies

AWAKE: proton-induced plasma wakefield acceleration

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aeorosols and clouds → implications on climate

COMPASS: hadron structure and spectroscopy

ISOLDE: radioactive nuclei facility

NA61/Shine: heavy ions and neutrino targets

NA62: rare kaon decays

NA63: radiation processes in strong EM fields

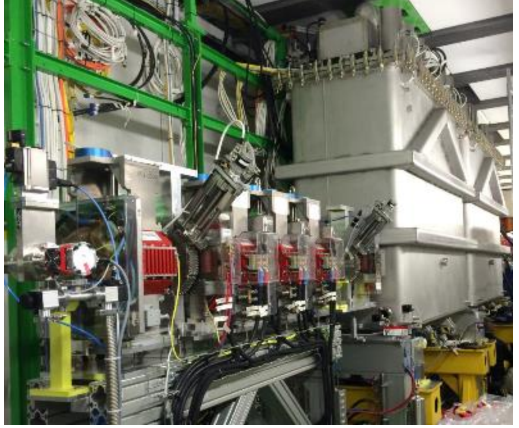
NA64: search for dark photons

Neutrino Platform: **ν** detectors R&D for experiments in US, Japan

n-TOF: n-induced cross-sections

UA9: crystal collimation

HIE - ISOLDE Status (Phase 1)

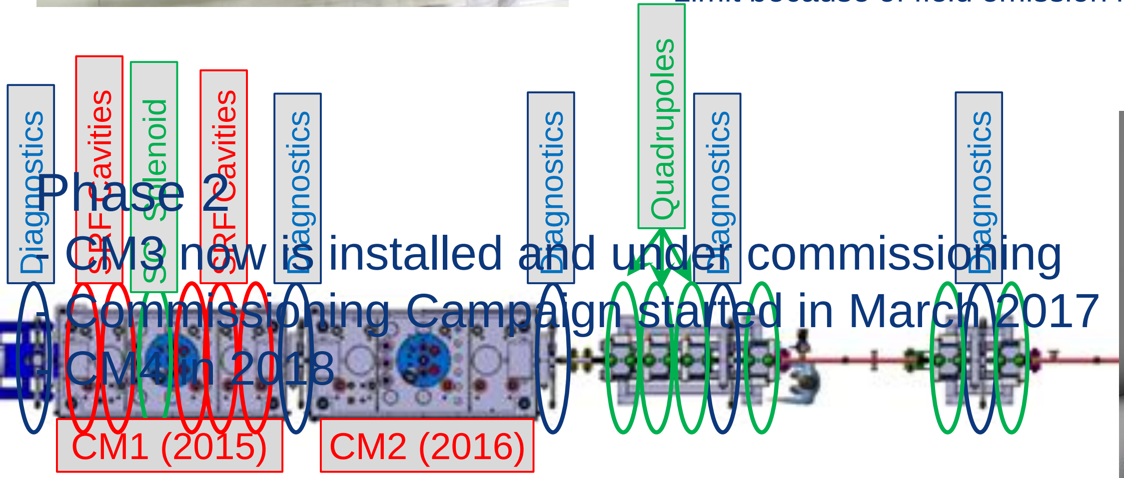


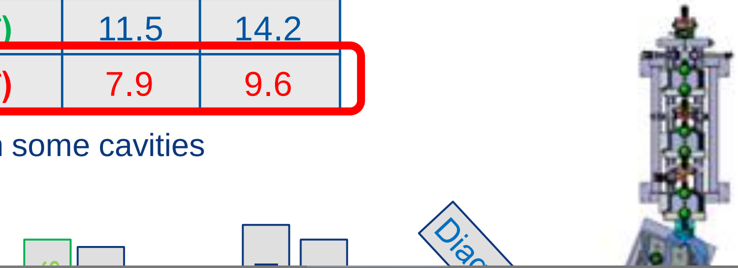
Phase 1B of HIE-ISOLDE was completed in 2016

- Two Cryo Module (CM) with 5 cavities each
- Two high energy beam transfer lines

Phase:	1A	1B (*)	2A	2B
Completed	**2015**	**2016**	2017	2018
Cryomodules	**1**	**2**	3	4
HEBTs	**2**	**2**	3	3
A/q = 2.5	**5.6**	**8.6 (7.7*)**	11.5	14.2
A/q = 4.33	**4.4**	**6.1 (5.6*)**	7.9	9.6

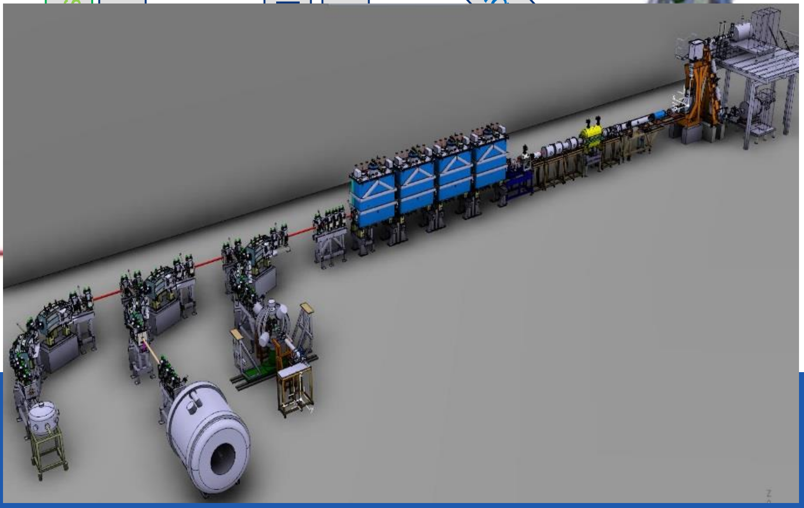
* Limit because of field emission in some cavities





Phase 2

- CM3 now is installed and under commissioning
- Commissioning Campaign started in March 2017
- CM4 in 2018



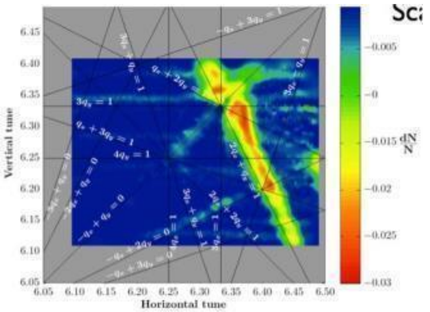
LS2 : (2019-2020), LHC Injector Upgrades (LIU)

LINAC4 – PS Booster:

– H^- injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
– New RF cavity system, new main power converters
– Increase of extraction energy from 1.4 GeV to 2 GeV

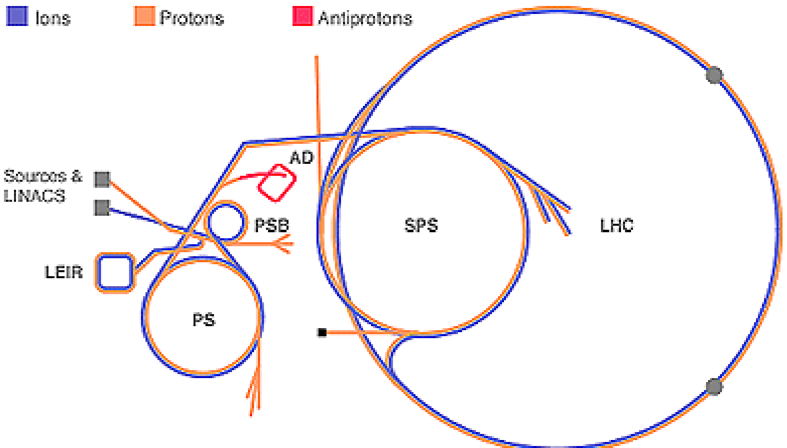
PS:

– Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
– Transverse resonance compensation
– New RF Longitudinal feedback system
– New RF beam manipulation scheme to increase beam brightness



SPS

– Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
– Impedance reduction, improved feedbacks
– Large-scale modification to the main RF system



These are only the main modifications and this list is far from exhaustive

Linac4 reached its energy goal – October 2016

The PIMS section

September-November 2016: Commissioning with beam of 12 PIMS accelerating structures (built in collaboration CERN-NCBJ-FZJ).

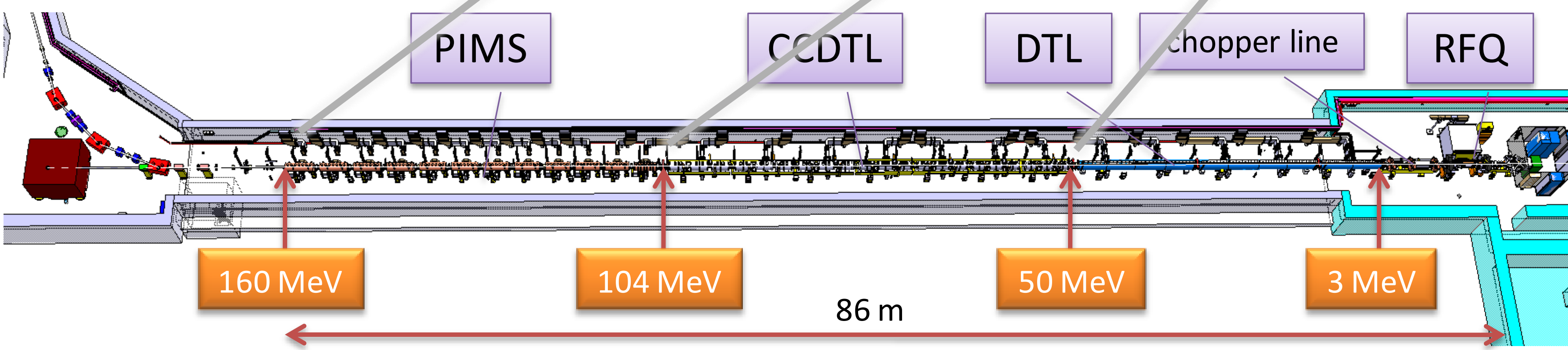
160 MeV design energy reached on 25.10. 2016

Installation of the last beam line element, August 2016

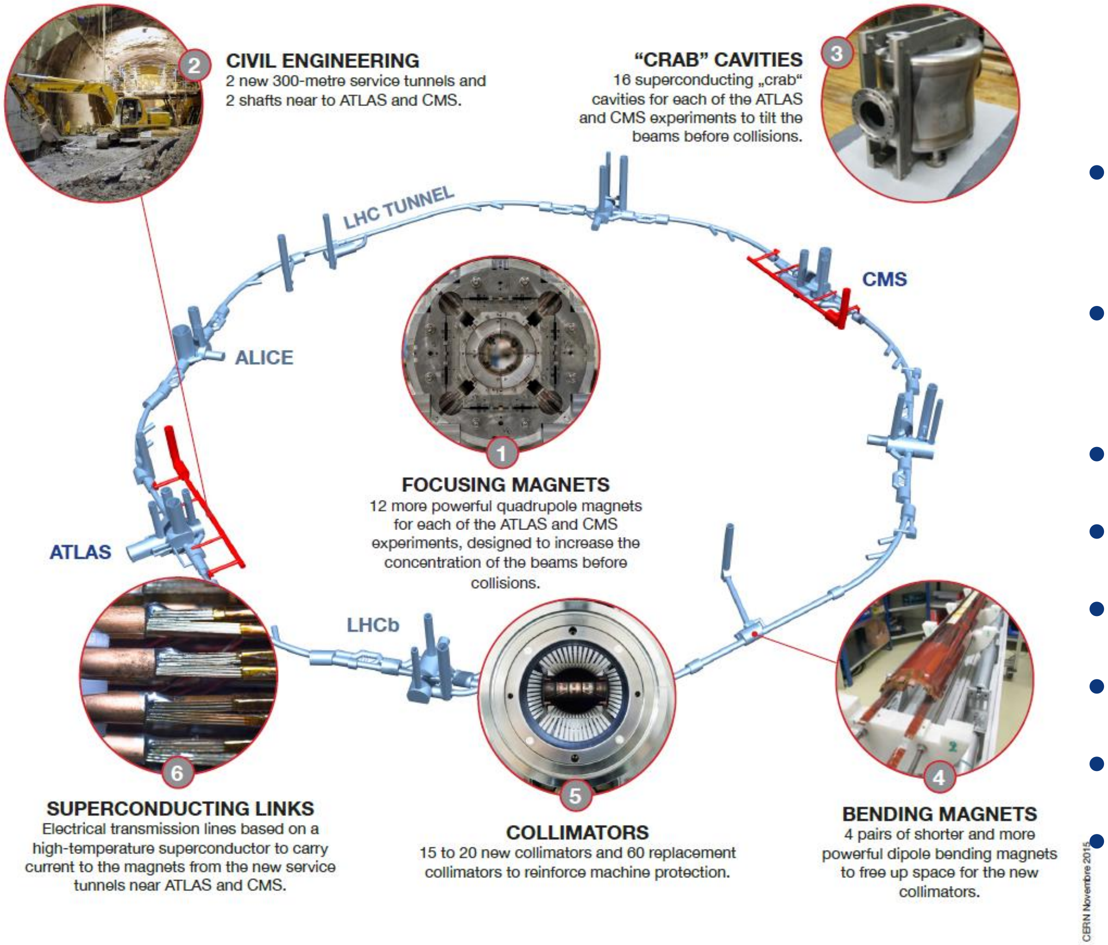
October 2016
160 MeV

June 2016
107 MeV

November 2015
50 MeV



The HL-LHC Project



- **New IR-quads Nb_3Sn (inner triplets)**
- **New 11 T Nb_3Sn (short) dipoles**
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Squeezing the beams: High Field SC Magnets

Quads for the inner triplet

Decision 2012 for low-β quads

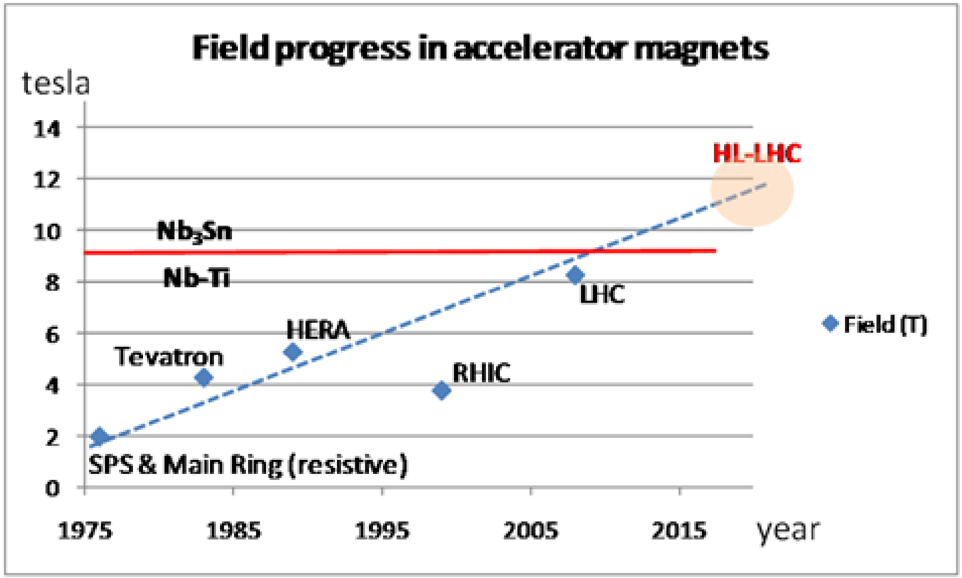
Aperture ∅ 150 mm – 140 T/m

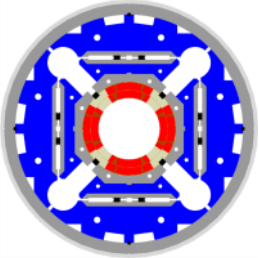
(B_{peak} ≈12.3 T)

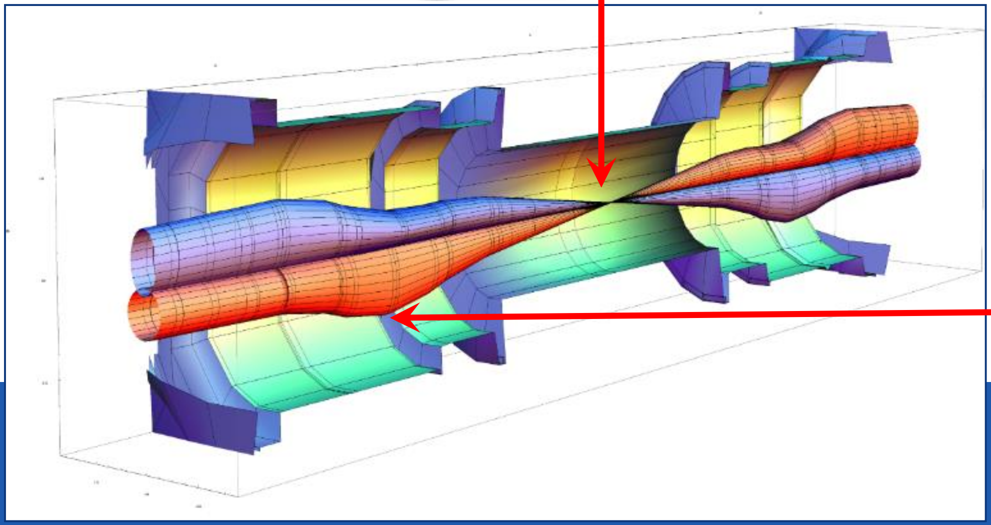
operational field, designed for 13.5 T

=> Nb_3Sn technology

(LHC: 8 T, 70 mm)







	$\beta_{triplet}$	Sigma triplet	β*	Sigma*
Nominal	~4.5 km	1.5 mm	55 cm	17 um
HL-LHC	~20 km	2.6 mm	15 cm	7 um

Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

- # enabling a total integrated luminosity of **3000 fb^{-1}**
- # implying an integrated luminosity of **250-300 fb^{-1} per year**,
- # design for **$\mu \sim 140$ (~ 200)** (➔ peak luminosity of **5 (7) 10^{34} cm^{-2} s^{-1}**)
- # design equipment for 'ultimate' performance of **7.5 10^{34} cm^{-2} s^{-1}** and **4000 fb^{-1}**

=> Ten times the luminosity reach of first 10 years of LHC operation

LHC Upgrade Goals: Performance optimization

Luminosity recipe :

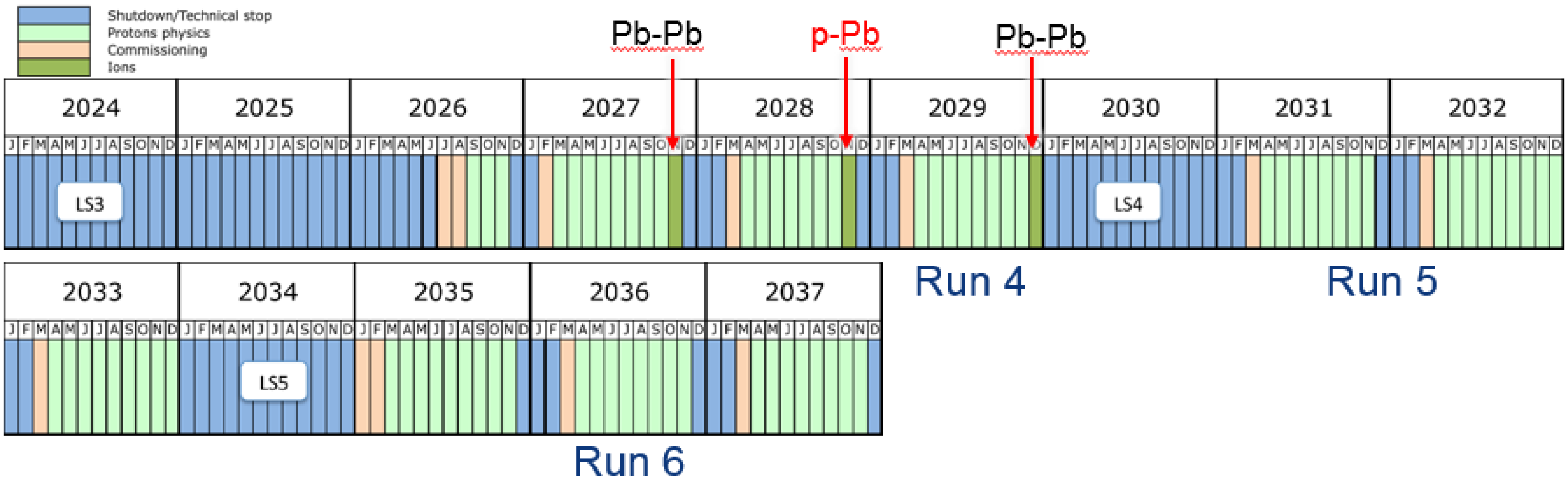
$$L = \frac{n_b \times N_1 \times N_2 \times g \times f_{rev}}{4 p \times b^* \times e_n} \times F(f, b^*, e, s_s)$$

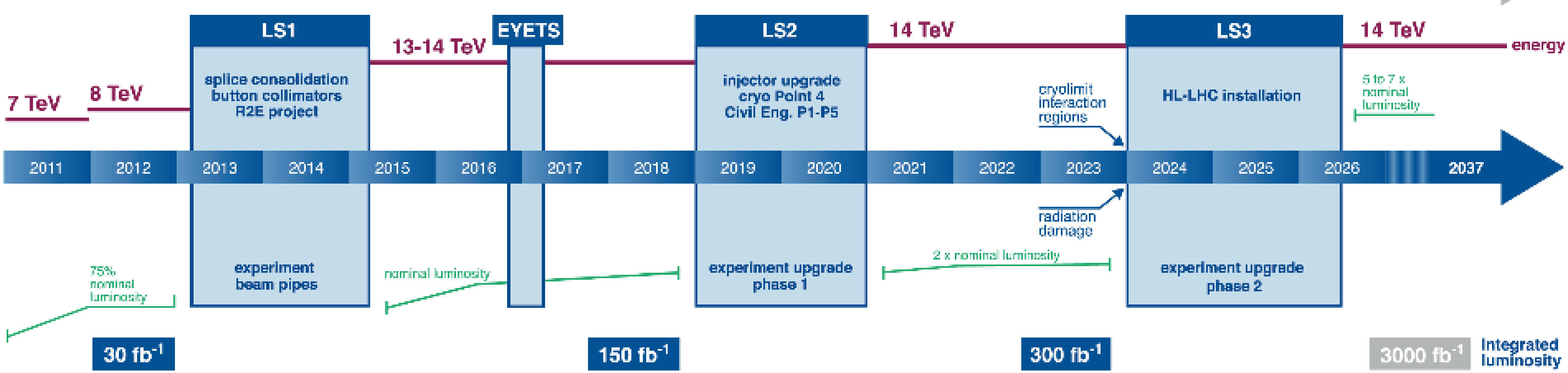
- ➔ 1) maximize bunch intensities ➔ Injector complex
- ➔ 2) minimize the beam emittance LIU ⇔ IBS
- ➔ 3) minimize beam size (constant beam power); ➔ triplet aperture
- ➔ 4) maximize number of bunches (beam power); ➔ 25ns
- ➔ 5) compensate for 'F'; ➔ Crab Cavities
- ➔ 6) Improve machine 'Efficiency' ➔ minimize number of unscheduled beam aborts

HL-LHC project

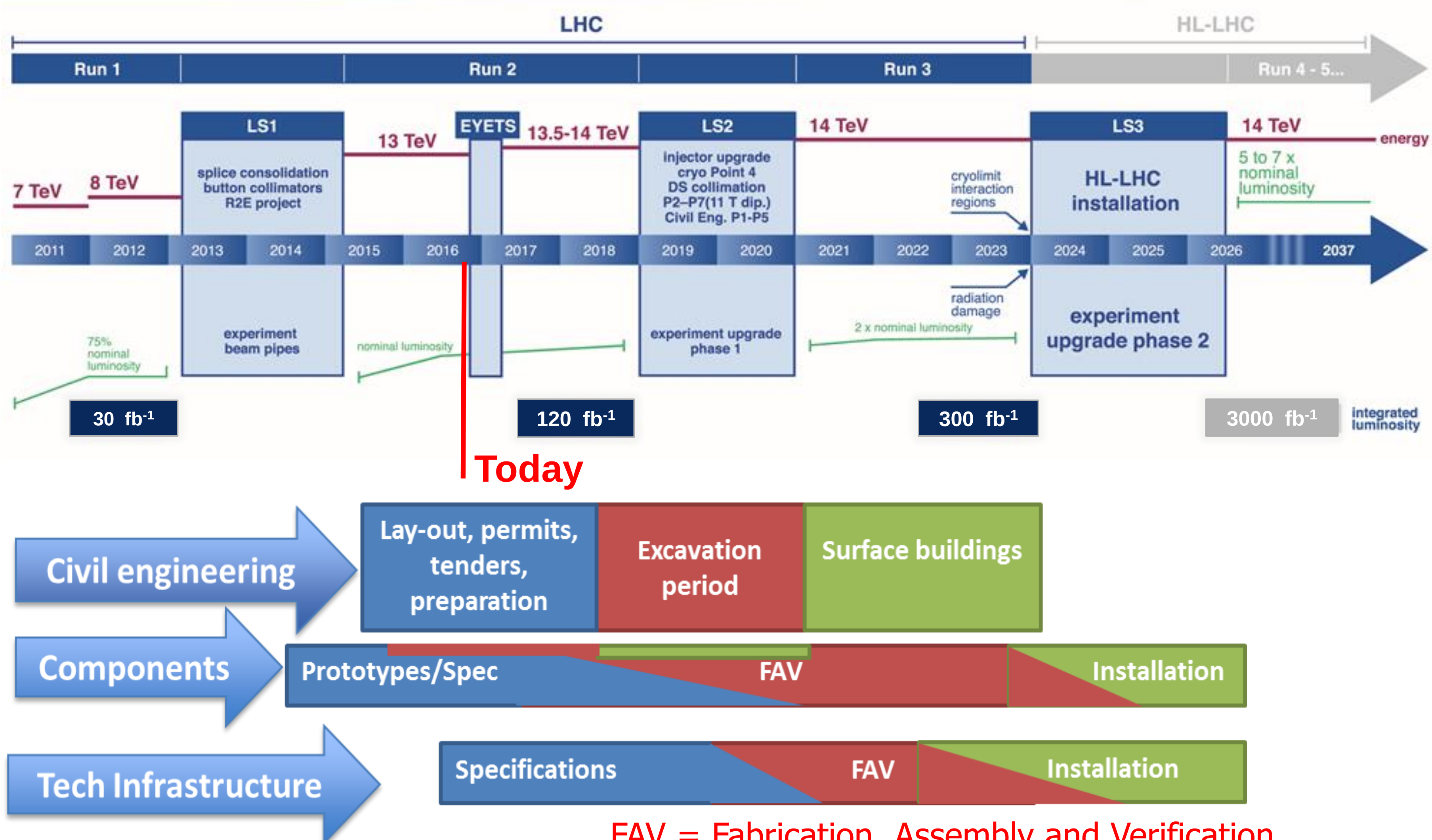
Formal approval by CERN Council (June 2016)

Cost to Completion
Material : 950 MCHF
Personnel: 1600 FTE-years





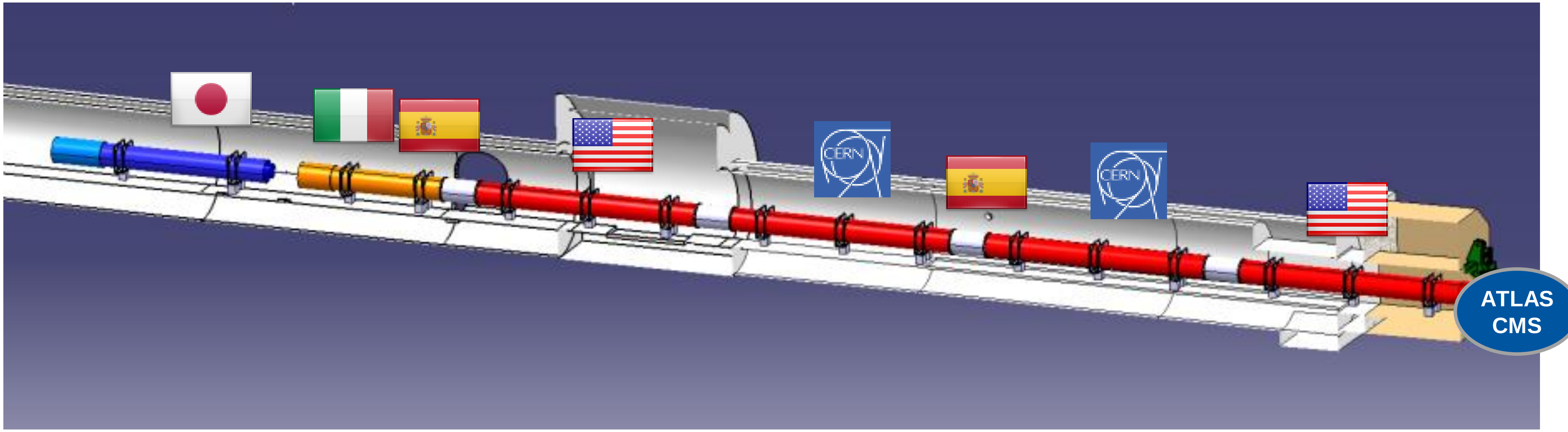
LHC / HL-LHC Plan

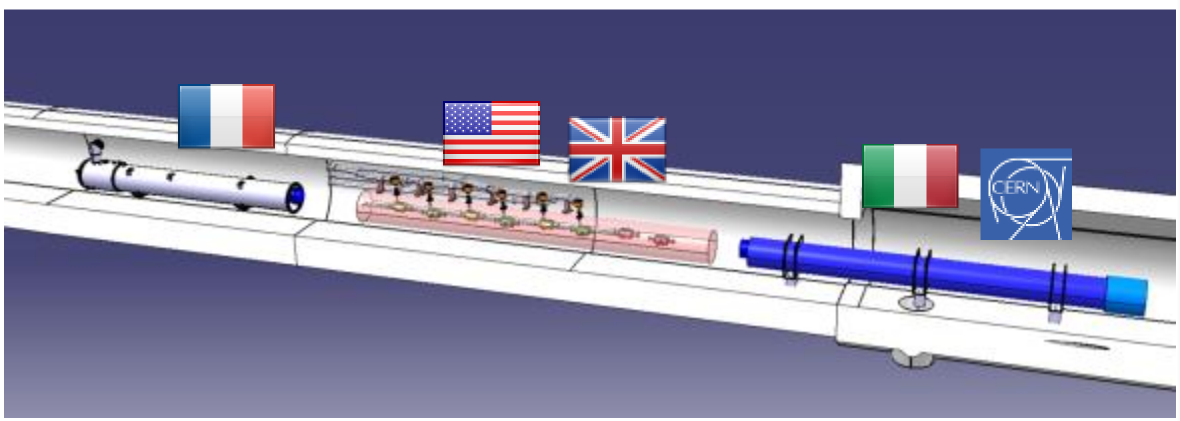


FAV = Fabrication, Assembly and Verification

In-kind contributions and collaborations for design, prototypes, production and tests

Discussions are ongoing with other countries, e.g Canada,…





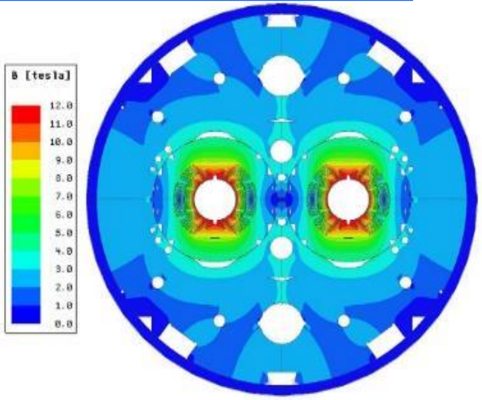
Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

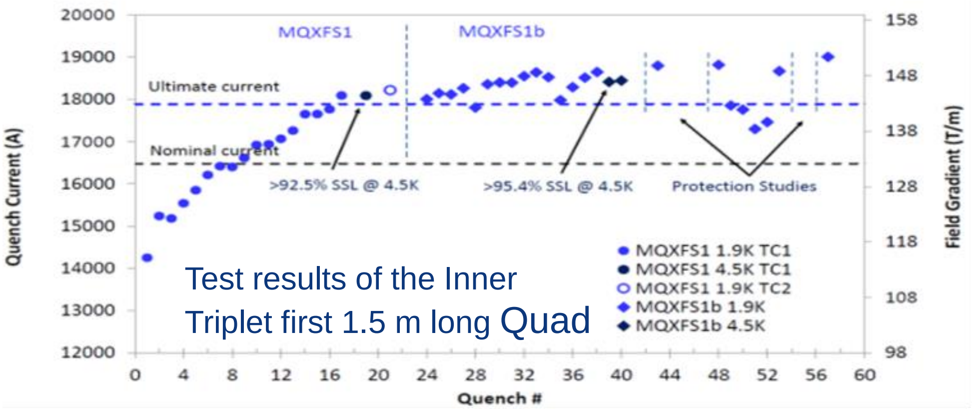
HL-LHC Main achievement 2016

The 11 T dipole 2 m long model reached a B_{max} of 12.5 T



Cross section of the 11 T dipole

Test of the first full cross-section (150 mm aperture) Triplet Quadrupole, 1.5 m long, half CERN, half USA: it went beyond ultimate ($B_{max\ eq.}$ of 12.5 T)



Test results of the Inner Triplet first 1.5 m long Quad

Completion of the first Crab Cavity, type Double Quarter Wave at CERN just before Christmas!

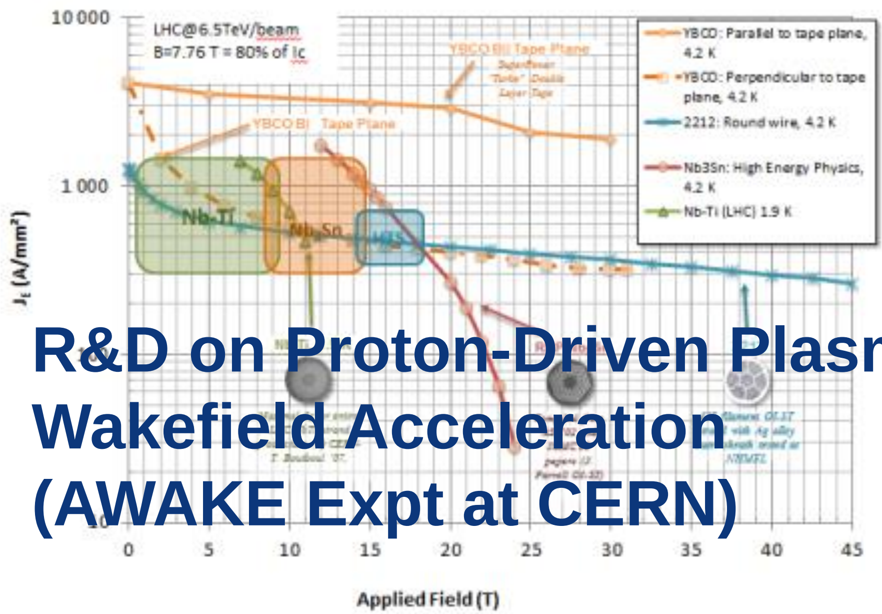
First Crab Cavity produced at CERN

“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”

CERN should undertake design studies for accelerator projects in a global context,

*with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator **R&D programme**, including **high-field magnets** **and** **high-gradient accelerating structures**, **in collaboration with national institutes, laboratories and universities worldwide.***

HFM



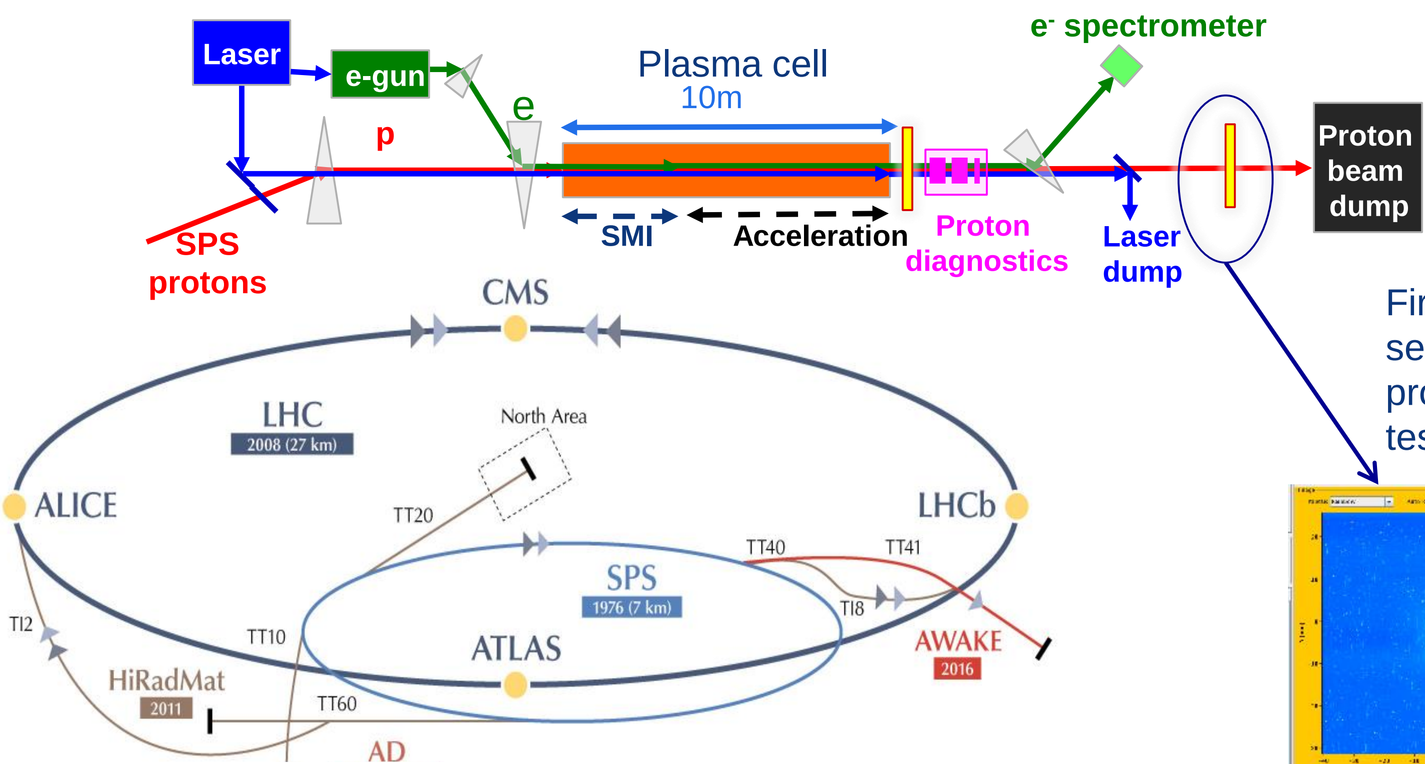
R&D on Proton-Driven Plasma Wakefield Acceleration (AWAKE Expt at CERN)

HGA

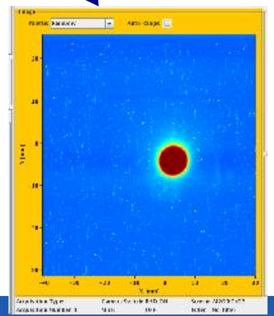
AWAKE

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

- Proof-of-concept experiment to **demonstrate** a **novel acceleration technique** that accelerates particles up to **three orders of magnitude** stronger than conventional methods.
  - Accelerate electrons of **several GeV/m**
- Use the **SPS proton beam** to generate powerful wakefields in a **10m long plasma**.
- Wakefields **accelerate externally injected electron** beam.
- Experiment has started end **2016**.

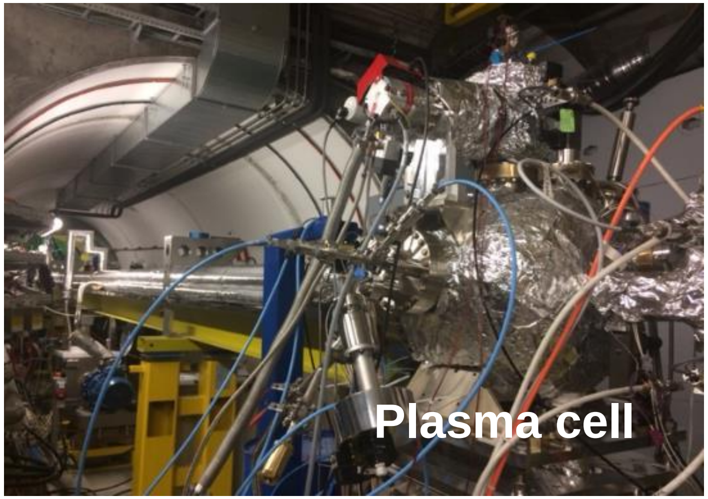


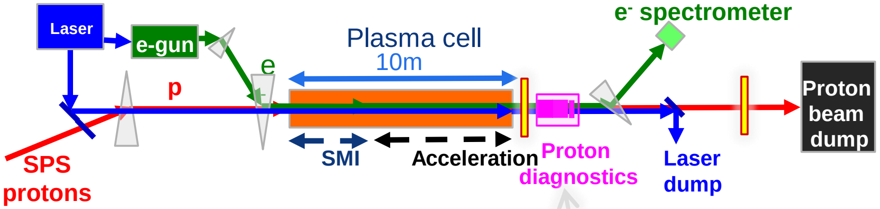
First proton beam sent to AWAKE for proton beam line tests (16 June 2016)

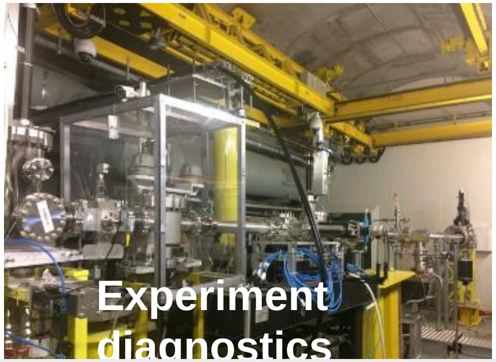


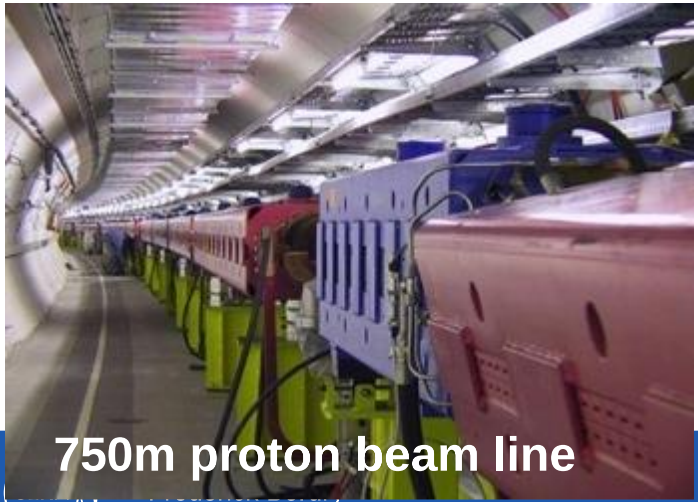
AWAKE

- Facility considerably modified for the AWAKE experiment.
- Proton and laser beam line installed and commissioned, matching all specifications.
- Experiment diagnostics installed and tested.
- Plasma cell installed and hardware commissioned.
- Synchronization of SPS beam with AWAKE laser with 20 ps accuracy.

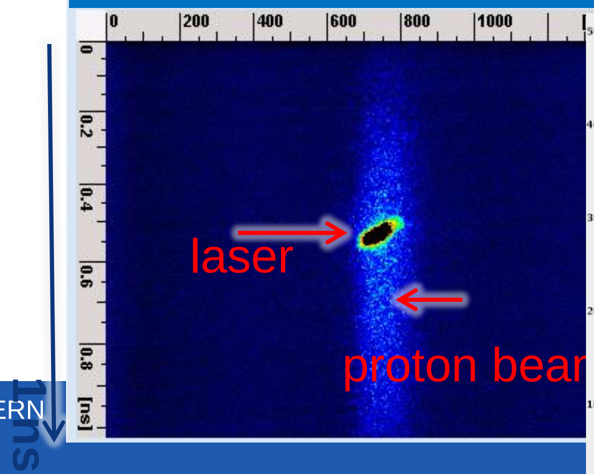


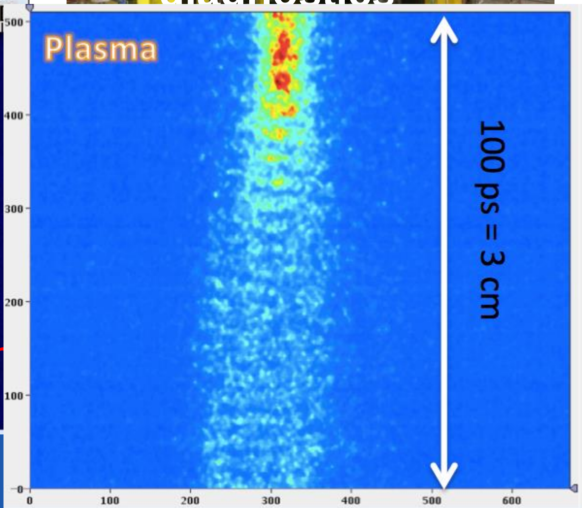




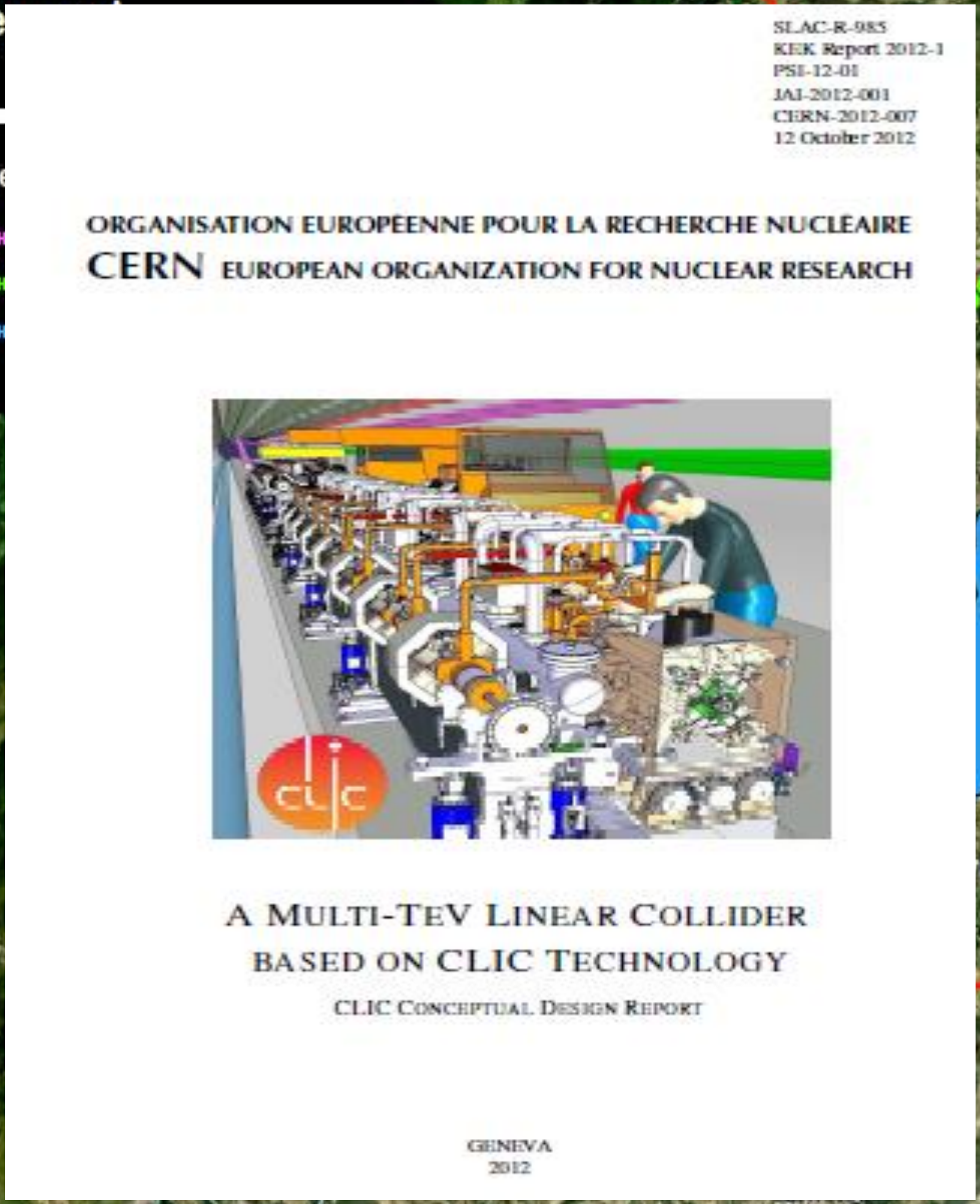


Measurement of proton and laser synchronization





CLIC Multi-TeV Linear Collider



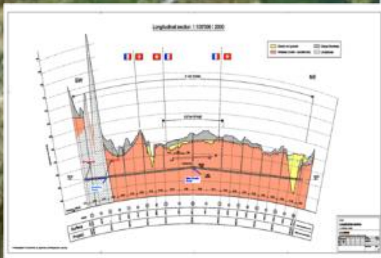
SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

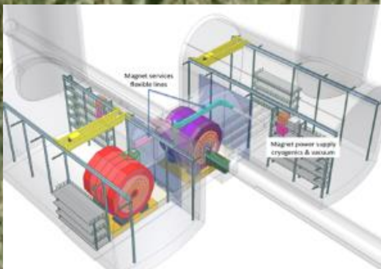
A MULTI-TEV LINEAR COLLIDER BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

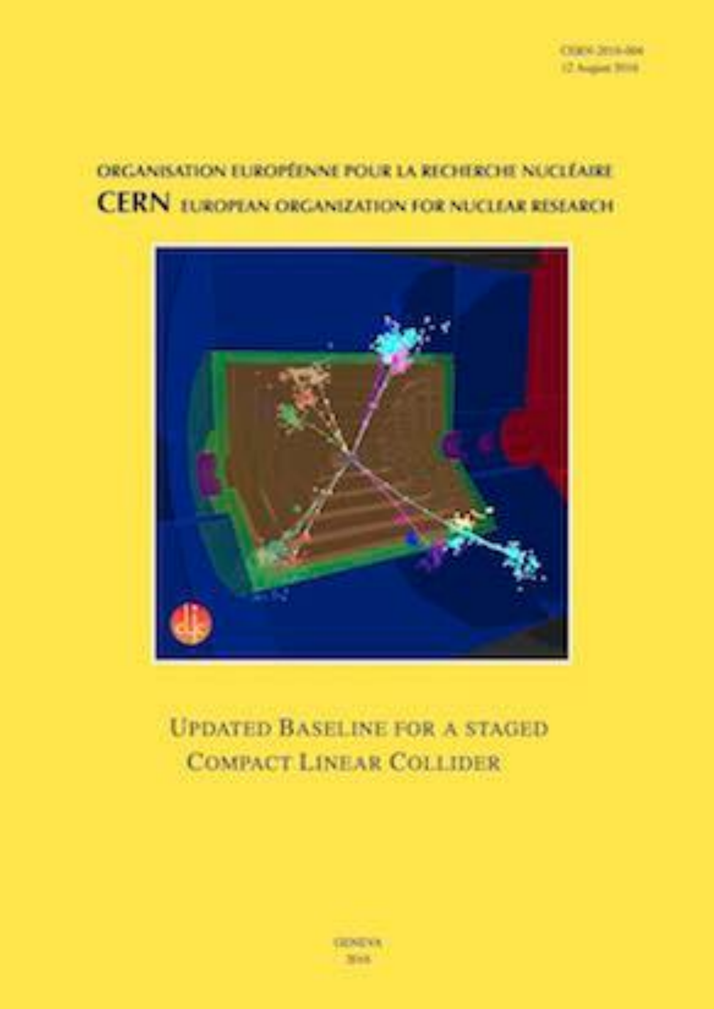


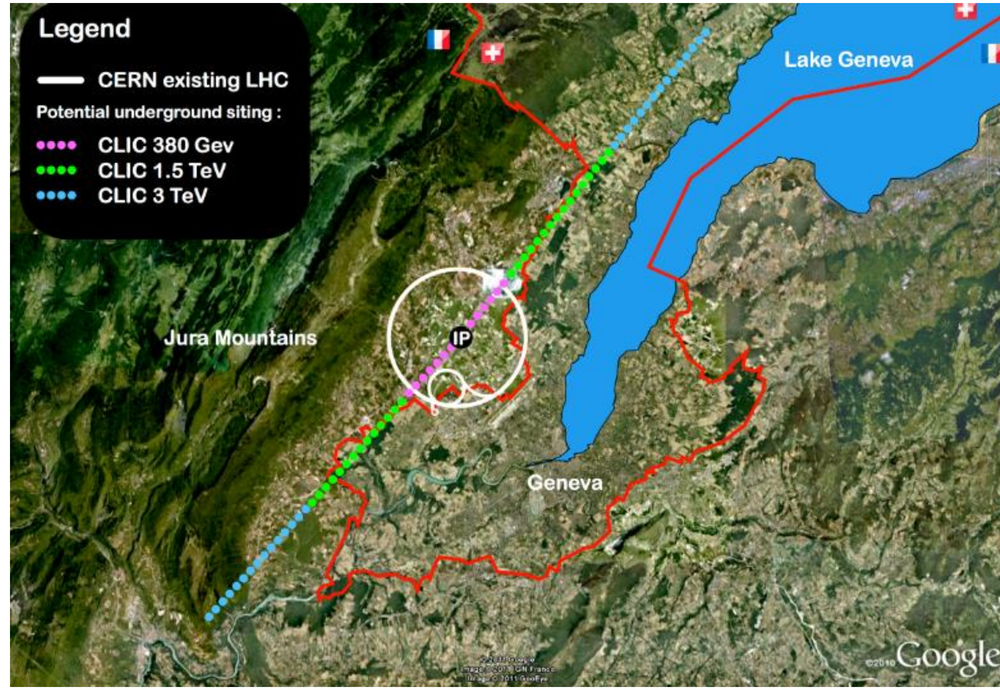
Tunnel implementations (laser straight)

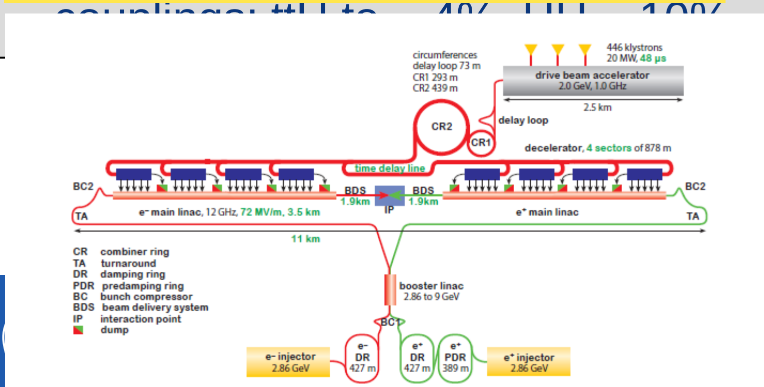


Central MDI & Interaction Region

Compact Linear Collider (CLIC)







Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

CLIC Collaborations

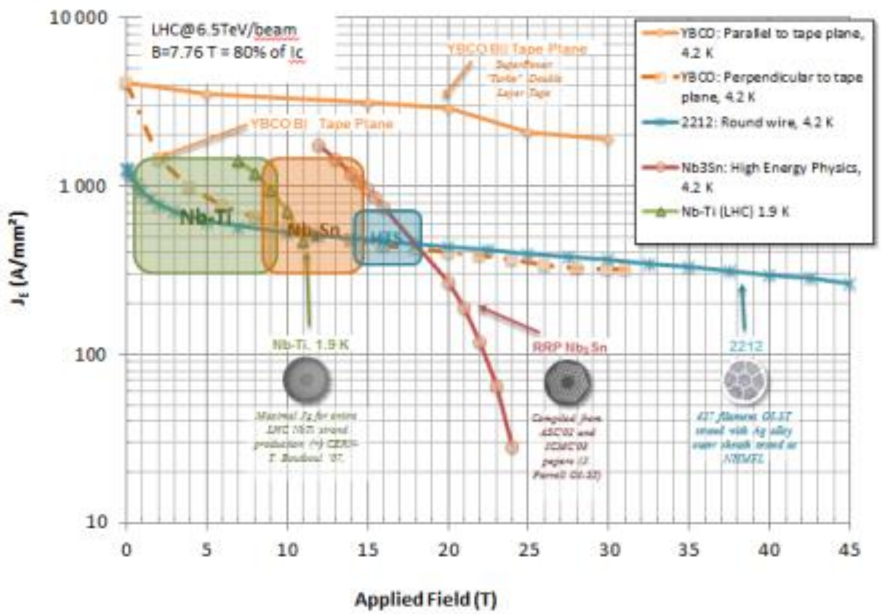
31 Countries – over 70 Institutes

“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”

CERN should undertake design studies for accelerator projects in a global context,

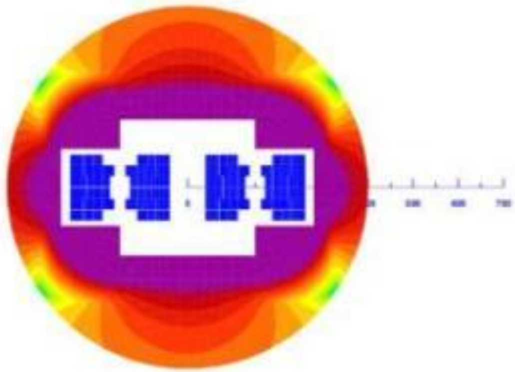
*with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator **R&D programme**, including **high-field magnets and high-gradient accelerating structures**, **in collaboration with national institutes, laboratories and universities worldwide.***

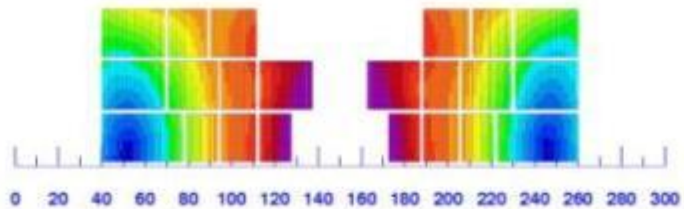
HFM



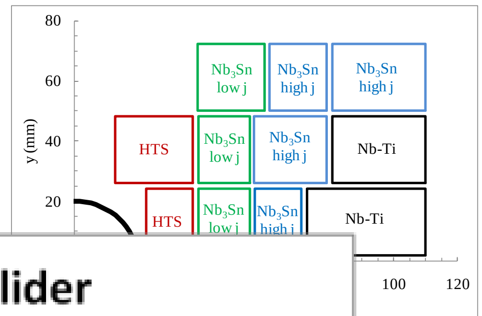
HGA

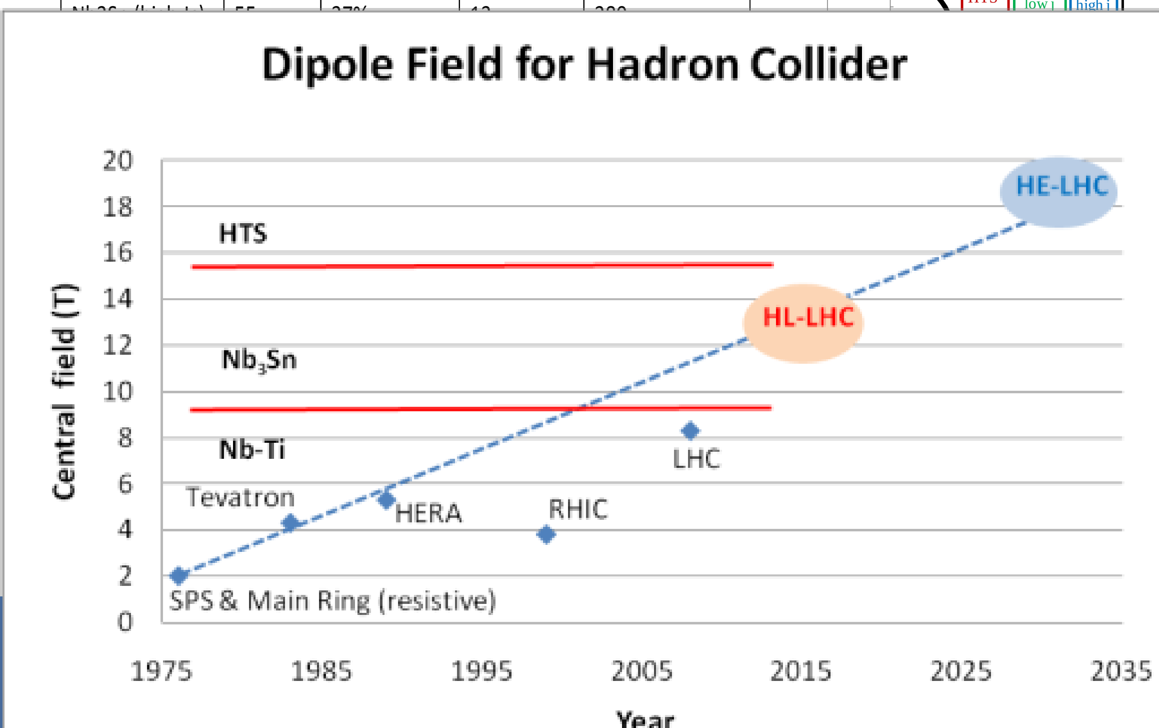
Malta Workshop: **HE-LHC @ 33 TeV c.o.m.**
14-16 October 2010





Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380





Magnet design (20 T): very challenging but not impossible.

300 mm inter-beam

Multiple powering in the same magnet (and more sectioning for energy)

Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam .

Otherwise limit field to 15.5 T for 2x13 TeV

Higher INJ energy is desirable (2xSPS)

beam screen at 60 K.

mping time.

ching 2x10^{34} appears reasonable.

handling for INJ & beam dump:

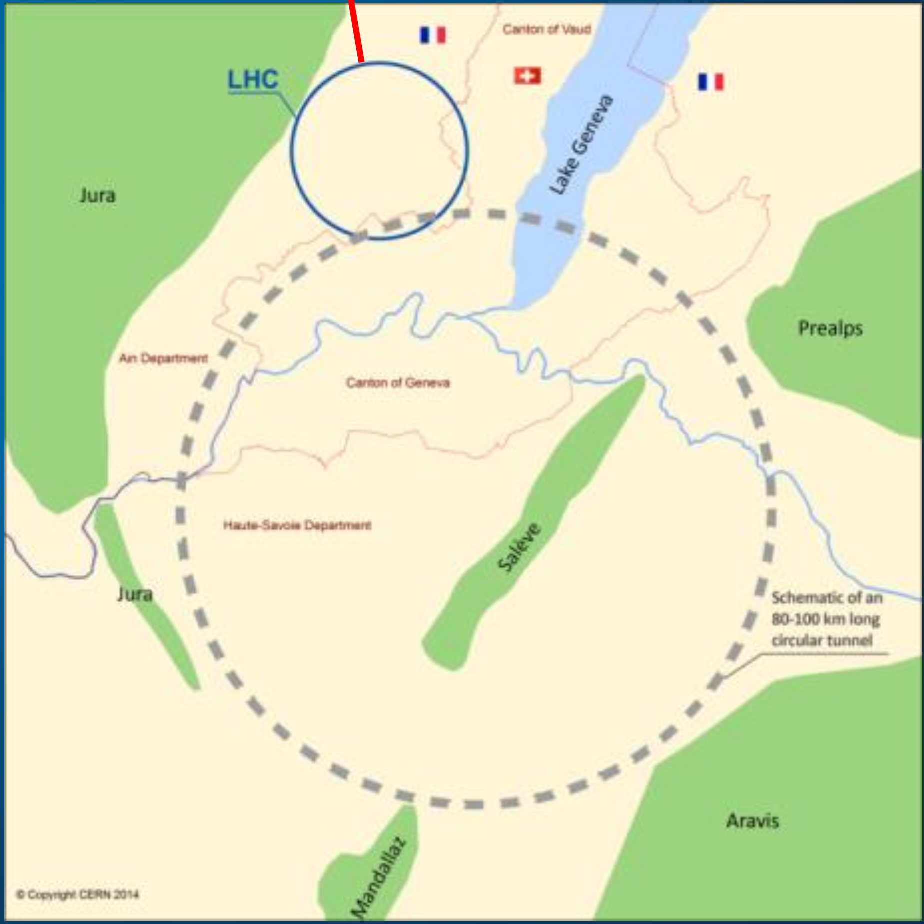
ice more room for LHC kickers.

Future Circular Collider

First studies on a new 80 km tunnel in the Geneva area

High Energy-LHC :33 TeV with 20T magnets

- **42 TeV** with **8.3 T** using present LHC dipoles
- **80 TeV** with **16 T** based on Nb_3Sn dipoles
- **100 TeV** with **20 T** based on HTS dipoles



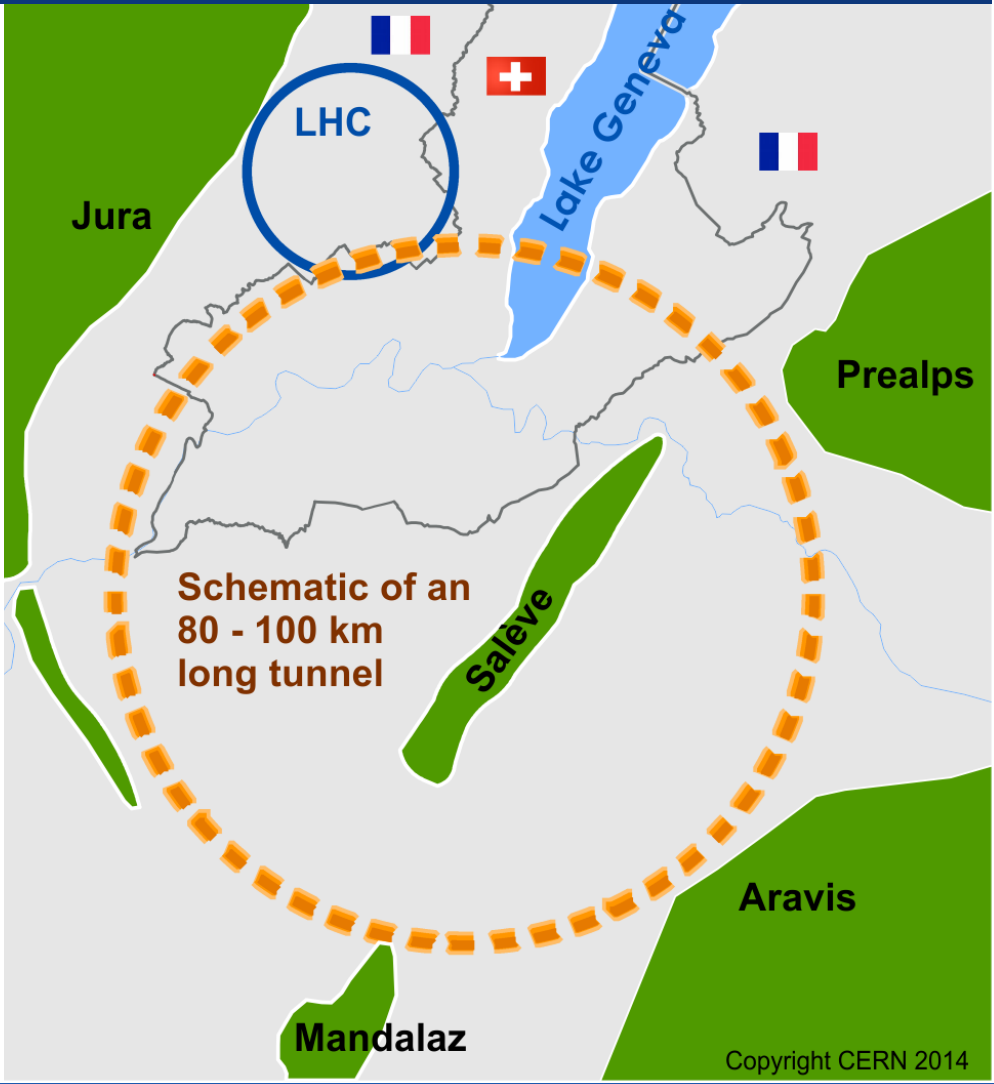
Future Circular Collider Study
Goal: CDR for European Strategy Update 2018

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



collaboration & industry relations


FCCWEEK2017
Future Circular Collider Conference
BERLIN, GERMANY
29 MAY - 02 JUNE
fccw2017.web.cern.ch
IEEE CSC
DPG
DESY

Conclusion

- **CERN is presently exploiting the physics potential of the LHC**
- **After the long shutdown LS1 the LHC operates at 13 TeV (2015-2016) and later to study when to increase towards 14 TeV (2016-2023).**
  => Goal 300 fb^{-1}
- **The approved high luminosity project HL-LHC will allow to collect ten times more data (2026 - mid 2030ies) => Goal of 3'000 fb-1**
- **Depending on the physics findings of the LHC "precision" e+e- linear colliders might be built in Japan (ILC) or at CERN (CLIC: 380 GeV,…, 3 TeV)**
- **CERN is hosting a study performed in international collaboration for a Future Circular Colliders in the Geneva area with a circumference of 80 – 100km:**
  - **hh-collider (FCC-hh) defining the infrastructure requirements**
  - ***e+e- collider (FCC-ee) as potential intermediate step***
  - ***e-h (FCC-eh) option***
  - **HE-LHC is also a possible option (staged approach): 16T-20T High Field Magnets in the present LHC tunnel**

Thanks for your attention

www.cern.ch

"The task of the mind is to produce future"
Paul Valéry

FCC-hh Key Parameters

Parameter	FCC-hh	LHC
Energy [TeV]	**100 c.m.**	**14 c.m.**
Dipole field [T]	**16**	**8.33**
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [$cm^{-2}s^{-1}$]	5-10 x 10^{34}	1 x 10^{34}
Energy/beam [GJ]	**8.4**	**0.39**
Synchr. rad. [W/m/apert.]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

Preliminary, subject to evolution

discharge 330 $\mu s \Rightarrow$ 24 TW

FCC-ee Key Parameters

Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	16700	1360	98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	28	6	1.8	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchr. Power [MW]	**100**			**22**
RF Voltage [GV]	2.5	5.5	11	3.5

Preliminary, subject to evolution

22 MW at LEP2